FINAL REPORT

TO THE OFFICE OF NAVAL RESEARCH

ONR GRANT N00014-89-J-1257

"Q TOMOGRAPHY IN OCEANIC CRUST"

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TOTAL AWARD: $180,120

PRINCIPAL INVESTIGATOR:

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PROJECT SUMMARY

Q TOMOGRAPHY IN OCEANIC CRUST

Long-Term Scientific Objectives

The broad objectives that guided this project were to characterize the structure and evolution of young oceanic crust and lithosphere, to assess the nature of lateral heterogeneity of oceanic crust and its effect on the propagation of seismic energy along crustal paths, and ultimately to relate observations of heterogeneity to causative geological processes.

Project Objectives

This project was aimed at an understanding of the Q structure of oceanic crust, the lateral variability of that structure, the relationship between Q and seismic velocity within oceanic crust, and the effect of both the mean structure and the superimposed variations on the mode and efficiency of seismic energy propagation. Specifically, we applied seismic tomographic techniques to determine quantitatively the three-dimensional seismic attenuation structure of the oceanic crust, with specific application to an existing data set from a tomography experiment conducted on the East Pacific Rise with a network of ocean-bottom seismometers and hydrophones.

Project Accomplishments

The seismic tomography experiment was carried out at 9°30'N on the East Pacific Rise at a location where multi-channel seismic reflection data had suggested the presence of a thin, shallow crustal magma chamber beneath the rise axis. A total of 480 explosive shots of uniform size (54.5 kg), construction, and depth of detonation were recorded by 15 ocean bottom hydrophones and seismometers. A three-dimensional velocity model obtained from this data set using delay time tomography confirmed the presence of a low-velocity zone at 2 km depth beneath the rise axis and resolved significant along-axis variations in the magnitude of this anomaly. Our approach to attenuation tomography utilized the velocity structure and ray paths obtained from delay time tomography and spectral information within the waveform following the first crustal arrival.

The power spectrum of each waveform can be written

$$P(f) = P_s(f)\, P_c(f)\, P_i(f) \qquad (1)$$

where $P_s(f)$ is the source spectrum, $P_c(f)$ is the crustal transfer function, and $P_i(f)$ the instrument response. Both the instrument response and the source signature, which was measured in a separate experiment, are accurately known for this data set. For each record, the smoothed power spectrum P(f) was obtained from data immediately following the first arrival using the method of overlapping windows, and a correction was applied for the instrument response and the source spectrum to obtain an estimate of $P_c(f)$ For each crustal path, the quantity t* is defined by

$$t^* = \int_{path} \frac{ds}{VQ} \qquad (2)$$

where V is the velocity and Q the quality factor. We estimated t* from the power spectrum $P_c(f)$ of a waveform using the relationship

$$\frac{d \ln[P_c(f)]}{df} = -2\pi t^* \qquad (3)$$

The estimate of t* and an associated uncertaintywere obtained by a least squares fit of a straight line to the power spectrum. In practice such estimates included not only the effects of anelasticity but also scattering and hence were measures of apparent rather than intrinsic attenuation.

To better understand the nature of seismic propagation on the East Pacific Rise and in particular to assess the importance of errors in wave paths, multipathing, and scattering we conducted a two-dimensional synthetic study using a finite difference method. The finite difference technique provides a means for calculating the full waveform solution in a non-attenuative medium and hence is an ideal method for assessing the importance of multiple phases and frequency-dependent non-anelastic effects. While computational limitations prohibited the investigation of three-dimensional structures, a two-dimensional study provided useful insights into the importance of scattered energy. Solutions obtained for sources at a variety of ranges from the rise axis show a fairly complex pattern of propagation that includes significant levels of scattering. For paths that cross the rise axis the first arrival always passes above the axial magma chamber at 1.5 km depth, but at large ranges the amplitude of this arrival is insignificant. At such ranges secondary arrivals, including diffractions from beneath the rise axis, a Moho turning phase, and PP arrivals dominate t* estimates obtained from the spectra of seismic waveforms. The results show that many of the approximate ray paths do not correspond to the path of the arrival that dominates t* estimates. While deterministic scattering may modify t* values, the effect can only account for a small fraction of the observed t* values.

On the basis of the improved understanding of seismic wave propagation obtained from the finite difference models and from an exact two-dimensional ray tracing algorithm, we systematically evaluated the attenuation tomography data set. t* estimates were obtained from 0.3-s and 0.6-s-long windows whose length and position were objectively chosen to maximize the contribution to t* from a single phase. Additional constraints were introduced into the ray tracing algorithm to ensure that each wave path was a reasonable approximation to the correct path of the phase. The final data set comprised over 3500 t* estimates and included direct crustal arrivals, diffractions from above and below the axial magma chamber, and Moho turning phases.

We successfully inverted this data set for both two- and three-dimensional models of attenuation across the rise axis. We parameterized Q^{-1} using a regular grid of 1-km-spaced nodes sheared vertically to conform with the seafloor. To constrain Q to physically realistic positive values, equation (1) was solved for $\ln(Q^{-1})$, a procedure which sacrificed linearity. A solution was obtained using an iterative maximum likelihood inversion scheme combined with a smoothest model method. Such a procedure simultaneously minimized the misfit between observed and predicted t* values and the perturbations to an initial $\ln(Q^{-1})$ model, thus insuring that the final model perturbations are strongly required by the data. The initial model was based on one-dimensional inversions of off-axis data. To account for errors in the instrument responses and for local variations in structure beneath receivers, a constant correction to t*, obtained from a two-dimensional inversion of the full data, was applied for each station.

The models resolved age-dependent variations in near-surface Q values which correlate with increased upper crustal velocity values observed near the rise axis. Off-axis Q values averaged over the upper 1 km are about 30, in good agreement with previous observations, while within a narrow region extending no more than about 2 km to either side of the rise axis values increase up to about 100. On the basis of laboratory measurements, the increase in near-surface attenuation with axial distance probably reflects increases in either porosity or degree of alteration. Models for axial magmatism suggest that the thickness of the high-porosity extrusive layer increases

significantly away from the rise axis. In addition, both tectonic and hydrothermal processes may contribute to lowering Q values within crust emplaced at the rise axis. Tectonic fracturing has been proposed as a mechanism to increase porosity. Outward of the axis, significant seafloor faulting commences on the flanks of the axial high, located about 2 km off axis at this location. Hydrothermal venting is confined to within a few hundred meters of the rise axis; circulation of high-temperature seawater may produce rapid increases in porosity and alteration as crust evolves off axis.

The inversions also imaged an axial low-Q region extending from 2 km depth to the base of the crust. The diffractions beneath the magma chamber, which sample the structure in the uppermost 1 km below the base of the magma chamber, resolved a 2-4 km-wide anomaly with a minimum well-resolved Q of about 30. In the lower crust the anomaly appears to broaden significantly. There is a trade off between the width of the anomaly and the absolute Q values in this region, and the wave paths are not sufficiently well known to resolve detailed structure. However, the results show that axial Q values in the lower crust may range from 25-50 and thus are very similar to the values resolved at shallower depths. Q values measured in the laboratory suggest that the minimum resolved Q values may be compatible with very small melt fractions, thus supporting a model of axial crustal structure that includes only a small crystal mush zone immediately beneath the magma chamber. However, since the uncertainties associated with comparisons of laboratory and seismic Q are large we cannot rule out models with higher melt fractions that extend throughout the crust.

Although two-dimensional axis-symmetric models fit the data well, along-axis variations in the low-Q anomaly can also be resolved. In the upper crust, the magnitude of the low-Q anomaly increases by about 25% toward the north of the experiment. Such a trend does not correlate with variations in the maximum negative velocity perturbation imaged by delay time tomography but correlates well with the velocity anomaly averaged over a 4-km-wide region extending from 2 to 3 km depth. In contrast the predominant feature in the lower crust and Moho transition zone is a southward increase in the levels of attenuation which correlates with a similar increase in delay times.

A list of all publications, book chapters, theses, and published abstracts of oral presentations supported by this project follows. Copies of papers published and in review are attached.

SUMMARY OF ACTIVITY ON ONR GRANT N0014-89-J-1257
FISCAL YEARS 1990-1994

a. Papers submitted to refereed journals, but not yet published

Wilcock, W.S.D., S.C. Solomon, G.M. Purdy, and D.R. Toomey, The seismic attenuation structure of the East Pacific Rise near 9°30'N, J. Geophys. Res., submitted, 1995.

b. Papers published in refereed journals

Toomey, D.R., G.M. Purdy, S.C. Solomon and W.S.D. Wilcock, The three-dimensional seismic velocity structure of the East Pacific Rise near latitude 9°30'N, Nature, v. 347, 639-645, 1990.

Wilcock, W.S.D., S.C. Solomon, G.M. Purdy, and D.R. Toomey, The seismic attenuation structure of a fast-spreading mid-ocean ridge, Science, v. 258, 1470-1474, 1992.

Wilcock, W.S.D., D.R. Toomey, G.M. Purdy, and S.C. Solomon, The renavigation of Sea Beam bathymetric data between 9°N and 10°N on the East Pacific Rise, Mar. Geophys. Res., v. 15, 1-12, 1993.

Wilcock, W.S.D., M.E. Dougherty, S.C. Solomon, G.M. Purdy, and D.R. Toomey, Seismic propagation across the East Pacific Rise: Finite-difference experiments and implications for seismic tomography, J. Geophys. Res., v. 98, 19913-19932, 1993.

c. Books or chapters submitted or in press

None

d. Books or chapters published

Solomon, S.C., and D.R. Toomey, The structure of mid-ocean ridges, Ann. Rev. Earth Planet. Sci., v. 20, 329-364, 1992.

e. M.S. or Ph.D. theses

Wilcock, W.S.D., The seismic attenuation structure of the East Pacific Rise, Ph.D. thesis, 370 pp., MIT/WHOI Joint Program in Oceanography, Cambridge, Mass., 1992.

f. Invited presentations at scientific/technical society conferences

Toomey, D.R., G. M. Purdy, and S.C. Solomon, Tomographic evidence for thermal segmentation of the East Pacific Rise axis, Eos Trans. AGU, v. 71, 625, 1990.

Toomey, D.R., S.C. Solomon, and G.M. Purdy, Application of new tomographic methods to data from the East Pacific Rise near 9°30'N, in AGU 1991 Fall Meeting, Eos Trans. AGU, v. 72, Suppl., 494, 1991.

Wilcock, W.S.D., S.C. Solomon, G.M. Purdy, and D.R. Toomey, The near-surface attenuation structure at 9°30'N on the East Pacific Rise, in 1992 Spring Meeting, Eos Trans. AGU, v. 73, Suppl., 274, 1992.

Wilcock, W.S.D., S.C. Solomon, G.M. Purdy, and D.R. Toomey, The seismic attenuation structure of 0.00- to 0.35-My-old crust on the East Pacific Rise at 9°30'N, in 1992 Fall Meeting, Eos Trans. AGU, v. 73, Suppl., 592, 1992.

g. Contributed presentations at scientific/technical society conferences

Toomey, D.R., G. M. Purdy, and S.C. Solomon, Three-dimensional seismic structure of the East Pacific Rise at 9°30'N, Eos Trans. AGU, v. 70, 1317, 1989.

Wilcock, W.S.D., S.C. Solomon, and G.M. Purdy, Three-dimensional attenuation structure at 9°30'N on the East Pacific Rise, Eos Trans. AGU, v. 71, 628, 1990.

Toomey, D.R., S.C. Solomon, and G.M. Purdy, Deep crustal seismic structure beneath the East Pacific Rise near 9°30'N, Eos Trans. AGU, v. 71, 1636, 1990.

Wilcock, W.S.D., S.C. Solomon, G.M. Purdy, D.R. Toomey, and M.E. Dougherty, Seismic attenuation structure of the crust on the axis of the East Pacific Rise at 9°30'N, in Spring Meeting 1991, Eos Trans. AGU, v. 72, Suppl., 263, 1991.

Dougherty, M.E., W.S.D. Wilcock, and S.C. Solomon, Elastic wave propagation through an East Pacific Rise magma chamber, in AGU 1991 Fall Meeting, Eos Trans. AGU, v. 72, Suppl., 309, 1991.

Wilcock, W.S.D., M.E. Dougherty, S.C. Solomon, D.R. Toomey, and G.M. Purdy, Finite difference models of wave propagation at 9°30'N: An evaluation of tomographic images of attenuation, in AGU 1991 Fall Meeting, Eos Trans. AGU, v. 72, Suppl., 495, 1991.

Wilcock, W.S.D., S.C. Solomon, G.M. Purdy, D.R. Toomey, and M.E. Dougherty, Images of seismic attenuation at 9°30'N on the East Pacific Rise: Implications for the distribution of melt within the crust, in 1992 Spring Meeting, Eos Trans. AGU, v. 73, Suppl., 290, 1992.

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